Unsupervised Relation Detection using Automatic Alignment of Query Patterns Extracted from Knowledge Graphs and Query Click Logs

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Abstract

Traditional methods for building spoken language understanding systems require manual rules or annotated data, which are expensive. In this work, we present an unsupervised method for bootstrapping a relation classifier, which identifies the knowledge graph relations present in an input query. Unlike existing work, we utilize only one knowledge graph entity instead of two for mining relevant query patterns from query click logs. As a result, the mined patterns can be used to infer both explicit relations (where the objects of the relations are expressed in the queries) and implicit relations (where the objects of the relations are being asked about). Using only the mined queries, the final classifier achieves an F-measure of 55.5%, which is significantly higher than the previous unsupervised learning baselines.

Index Terms: conversational understanding systems, relation detection, search query click logs, unsupervised learning, semantic graph

1. Introduction

In a dialog system, the *spoken language understanding* (SLU) module receives transcribed speech queries and extracts their semantic information, which can be used for decision making and response generation [1, 2]. We focus on building a *relation detector*, which outputs all relations expressed in the query (e.g., *"Who played Jake Sully in Avatar"* has relations *acted by*, *character name*, and *movie name*). These relations are used to form queries to databases or knowledge graphs in order to generate an appropriate response [3].

Most approaches for building SLU systems depend on either complex hand-crafted rules, which require time and expertise to write, or supervised learning, which requires a large amount of human-annotated data. However, designers of SLU systems may reduce supervision by using external resources that relate natural language to some computable semantic structures. We focus on two resources: *knowledge graphs*, which represent relations between entities as large directed graphs, and *web search query click logs*, which link search queries to the URLs that the users click on.

In this work, we propose a totally unsupervised method for bootstrapping a relation detector. Instead of using manually annotated sentences, we acquire natural language queries in the domain of interest from search query click logs. Subsequently, we use knowledge graphs and URLs from the click logs to filter the queries and automatically label them with relations. Our previous work on relation detection [3] uses a similar distant supervision approach that automatically annotates sentences with the intended relations when both of the related entities appear in the search queries or web documents. However, such an approach only targets *explicit relations*, as it requires the subjects and objects of the relations to both be specified in the queries (e.g., the *director name* relation in *"Find Avatar movie directed by James Cameron"*), and hence makes limited use of related search queries. With our new methods, we can also infer *implicit relations*, where the values of the relations are being asked about and thus left unspecified (e.g., the *directed by* relation in *"Who made Avatar"*). Explicit and implicit relations are inferred with separate but related techniques: for explicit relations, we use knowledge graph entity-relation-entity triples to automatically label the objects of the relations, while for implicit relations, we consider the entities that can invoke the relations and leverage the query patterns mined from those entities. The final classifier which uses only the mined data achieves a micro F-measure of 55.5%, a large improvement over previous unsupervised learning baselines.

The rest of the paper is organized as follows. The next section formally introduces the task, knowledge graphs, and query click logs. Section 3 presents the relevant work that uses the same external resources. In Section 4 we describe our approach, the results of which are presented in Section 5. Finally, Section 6 concludes the paper.

2. Relation detection using knowledge graphs and query click logs

In this section, we describe the relation detection task and the resources we use to tackle the task: large-scale semantic knowledge graphs (e.g., Freebase [4]) and search query click logs.

2.1. Knowledge graphs

We focus on the relations that are present in *graphical knowledge bases*, or *knowledge graphs* for short. A knowledge graph, as illustrated in Figure 1, is a directed graph where each node represents an entity (e.g., *Avatar* or *James Cameron*) and each labeled edge represents a relation between two entities (e.g., *directed by*). Each entity belongs to one or more types (e.g., *Avatar* belongs to the *film* type), and each type has a schema specifying which relations should originate from the entities of that type (e.g., an entity of type *film* will have a *directed by* relation to an entity of type *film director*).

2.2. Relation detection task

We consider the *relation detection task*: given a transcribed natural language query, we want to determine all relations expressed in the query [3]. For example, both *"Show me movies*

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by James Cameron" and *"Who directed Avatar"* contain the relation *directed by*, but only the first query contains the relation *director name*. These relations can be regarded as building blocks toward full language understanding, since more complex representations of the query, such as SPARQL knowledge graph queries or semantic logical forms, will contain these relations.

2.3. Query click logs

To obtain natural language queries in an unsupervised fashion, we use *query click logs* (QCLs), which record the URL that each user chose in a search engine after issuing a query. Along the line of [5], we represent QCLs as a weighted undirected bipartite graph: the queries and the URLs form two sides of nodes, and the weight of the edge between a query node and a URL node indicates the number of users who issued the query and then clicked on the URL.

3. Related work

Earlier work on statistical spoken language understanding (SLU) employs supervised learning, typically treating intent detection as multi-class classification and slot filling as sequence labeling [6, 7]. The training data for these tasks is annotated according to a task-specific semantic representation [8]. To decrease the cost of acquiring and labeling training data, a group of studies has investigated methods to adapt generic semantic representations, associated annotated data, and clustering methods for training task-independent models [9, 10, 11].

Another research trend is the application of pre-existing structured data in language understanding. In particular, with the emergence of large knowledge bases (Freebase, Yago2, DBPedia, Satori), many systems rely on knowledge graphs for distant supervision. For example, given large text corpora (e.g., Wikipedia or ClueWeb), information extraction systems can find sentences containing pairs of entities with some target knowledge graph relation, and then use the extracted sentences to train a high-precision relation extractor [12, 13, 14]. Instead of large corpora, the Web can also be used to supply relevant sentences by scraping the search engine snippets when the pairs of entities are used as search queries [3]. The alignments between the sentences (surface forms) and the underlying knowledge graph relations can also be utilized in downstream tasks such as classifying relations for answering factoid question [15, 16, 17].

Besides knowledge graphs, query click logs have also been used to build SLU systems in an unsupervised fashion. QCLs were originally used to improve search results or suggest similar search queries [18, 19, 20], but as QCLs contain a large amount of text (search queries) with noisy semantic annotation (URLs), they are also used in many language understanding tasks such as acquiring related entities [21], clustering entities into semantic classes [22, 23], user intents detection [24], entity type classification [25], and knowledge acquisition [26]. In our previous work, the queries mined from QCLs are used as examples to classify query domains [27] and detect new query intents [28]. This work extends from the previous work by (1) using the relation model, which encompasses both intents and slots, (2) proposing methods for mining queries that require only one pivot entity instead of two, and (3) using aggregate pattern statistics of the queries in a novel way to detect both explicit and implicit relations.

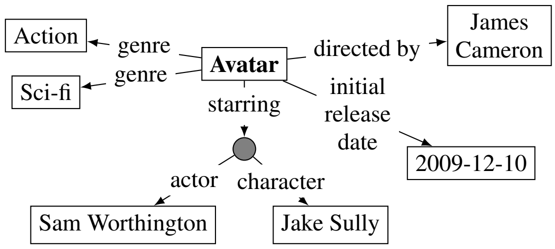

Figure 1: *A small portion of the knowledge graph. The gray circle is a mediator node representing an (*actor, character*) pair.*

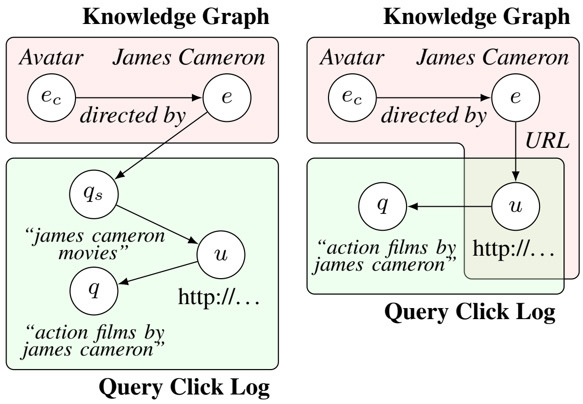

Figure 2: *Query mining. From a property entity e, we find the corresponding URLs from either the seed queries (left) or the knowledge graphs (right), and then mine the corresponding search queries from the QCL.*

4. Approach

We now describe our approach to unsupervised relation detection, which includes three major steps. First, we mine the queries related to the entities of interest from the query click logs (Section 4.1). Then, we use the queries to infer two types of relations, explicit (Section 4.2) and implicit (Section 4.3). Finally, the queries with inferred relations are used to train a combined relation classifier (Section 4.4).

4.1. Mining entities and queries

The first step of the pipeline is finding knowledge graph entities in the domain of interest. For example, in the movie domain, we want to find the list of all movies as well as their attributes (e.g., directors, actors, characters). We start by listing all entities of the *central type* corresponding to the desired dialog domain (e.g., Freebase *film* type for the movie domain). Then, for each entity e_c of the central type (e.g., from Figure 1, $e_c =$ *Avatar*), we compute the *property list* $P(e_c)$ of entities that are related to e_c. Formally, $P(e_c)$ includes:

- entities e with an incoming relation from e_c (e.g., $e =$ *James Cameron* via the relation *directed by*)
- entities e reachable from e_c within two relations via a mediator node (e.g., $e =$ *Jake Sully* via the relations *starring* and *character*)
- $e = e_c$ itself (e.g., $e =$ *Avatar*)

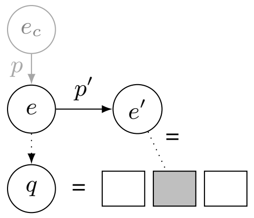

Figure 3: *Bootstrapping an explicit relation dataset D_E. When e' is contained in the query q, we infer that q has explicit relation p'.*

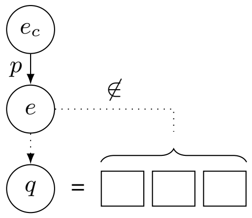

Figure 4: *Bootstrapping an implicit relation dataset D_I. When e is* not *contained in query q, we infer that q has implicit relation p.*

By combining the property lists $P(e_c)$ over all e_c, we get the list $\bigcup_{e_c} P(e_c)$ of all entities related to the dialog domain.

To find spoken-language sentences for training relation classifiers, we mine queries about each entity $e \in \bigcup_{e_c} P(e_c)$ from a query click log (QCL) using one of the two strategies as illustrated in Figure 2:

1. **Using URLs from seed queries.** For each entity e, we use simple templates to formulate *seed queries* q_s based on e (e.g. the entity *Action* of type *film genre* results in *"action movies"*, *"action films"*, etc.) and then retrieve the corresponding clicked URLs u from the QCL. Afterward, we find other queries q that link to the same URLs u in the QCL. By traversing from seed queries to URLs and then to other queries, we effectively perform a two-step random walk on the QCL graph [5].
2. **Using URLs from knowledge graphs.** Instead of getting URLs from seed queries, we observe that in knowledge graphs, most entities have several relations pointing to the URLs of either the official websites or the encyclopedic pages about the entities (e.g., Wikipedia pages). For each entity e, we mine such URLs u from Freebase and Bing Satori, and then find the queries q in the QCL that connect to the mined URLs u.

With either method, using the QCL as the query source has an advantage that a large amount of search queries are in question format, which is stylistically similar to spoken language queries. Unfortunately, a significant fraction of search queries turn out to be "keyword" queries composed of noun phrases entities [29]. To filter out such queries, one could employ a classifier that separates natural language queries from keyword queries [30]. In this work, we use a simpler technique derived from [31] by choosing only the queries with either stop words or words that signal spoken queries (e.g., *"show"*, *"list"*, *"want"*).

In the next sections, we explain how the filtered queries are used to create datasets for training relation classifiers.

4.2. Inferring explicit relations

Most queries explicitly specify the objects of some relations they contain. For example, the query *"Who played Jake Sully in Avatar"* specifies that the value of the relation *character name* is *Jake Sully*. We refer to such relations where the objects are explicitly specified as *explicit relations*. Our goal in this step is to automatically annotate explicit relations in the mined queries.

To infer explicit relations, we use the following observation: in a query q that links to a URL of an entity e, it is likely that q mentions either e or some other entities e' closely related to e. For instance, the query $q =$ *"Who played Jake Sully in Avatar"*, which is mined from the entity $e = e_c =$ *Avatar*, contains the entities $e =$ *Avatar* and $e' =$ *Jake Sully*. The presence of e and e' can be used to infer explicit relations. In the example above, since $e' =$ *Jake Sully* is related to *Avatar* via the path (*starring*, *character*), we can infer that the query contains the explicit relation *character name*. Similarly, the presence of $e =$ *Avatar* in q invokes the *movie name* relation.

From this intuition, we create a dataset D_E for training an explicit relation classifier. Figure 3 illustrates our method. For each query q mined for entity e, we use approximate string matching to find all related entities $e' \in P(e)$ such that the name of e' appears in q. Then, we translate the paths p' from e to e' into explicit relations (e.g., $p' =$ (*starring*, *character*) translates to *character name*). Note that by the definition of $P(e)$, we also allow e' to be e itself, in which case the corresponding explicit relation is the type of e (e.g., $e = e' =$ *Avatar* gives the relation *movie name*). As a by-product of this alignment process, we can also derive an automatic *slot annotation* of the query by annotating the occurrences of e' in q with the translated relations (e.g., *"Who played [Jake Sully]$_{\text{(character name)}}$ in [Avatar]$_{\text{(movie name)}}$"*).

We use 200,000 automatically labeled examples in our experiments. To balance the relation labels, we impose that half of the examples have the *movie name* relation while the other examples do not.

4.3. Inferring implicit relations

Implicit relations are the relations whose objects are being asked about and thus are left unspecified. For example, the query *"Who directed Avatar"* has the implicit relation *directed by* because it asks about the unspecified director's name.

To infer implicit relations, we use a property of the QCL illustrated by the following example. Consider queries of the form *"Who directed [movie name]."* Most of the time, users who enter such queries will click on the official or encyclopedic pages about the movie; however, occasionally some users will click on web pages about the *director* of the movie. In this case, we may infer that the query pattern *"who directed ..."* has the implicit relation *directed by*. More generally, if the entity e corresponding to the clicked URL does not appear in the query q, we may infer that the entity is likely the (missing) object of an implicit relation in the query.

Using the intuition above, we create a dataset D_I for training an implicit relation classifier as illustrated in Figure 4. Consider an entity $e \in P(e_c)$ and a query q mined for e. If the name of e does not appear in q, then we translate the path p from e_c to e into an implicit relation (e.g., $p =$ *directed by* in the example above translates to the *directed by* relation). To reduce noise, we filter out some out-of-domain queries by removing queries q that do not contain any entity related to e.

The implicit relation dataset D_I contains 340,000 examples. In addition to creating the dataset, we can also derive a list of generic *query patterns* for each implicit relation by collapsing entities $e' \in P(e)$ that appear in the queries into placeholders based on the path between e and e' (e.g., *"Who directed Avatar"* becomes *"who directed [film]"*). Table 1 shows several examples of good query patterns.

4.4. Combined classifier

After we obtain training data D_E for explicit relations and D_I for implicit relations, we train a combined relation classifier

movie type	acted by
[actor] and [actor] movie who played [character] in [film] [film] [profession] [actor] as [character]	[profession] in [film] [character] from [film] who played [character] cast of [film]
directed by	**has character**
director of [film] who directed [film] [film] the movie [film] director	characters in [film] [actor] in [film] girl from [film] the cast of [film]

Table 1: *Several derived query patterns for implicit relations.*

URL source	Classifier	n-grams	n-grams + w-gaz
-	Majority	27.6	
-	[33]	43.3*	
seed	Explicit (D_E)	34.0	36.2
seed	Implicit (D_I)	16.8	17.0
seed	Combined	43.1	43.0
KG	Explicit (D_E)	39.6	42.7
KG	Implicit (D_I)	29.3	29.3
KG	Combined	53.8	**55.5**
-	Supervised	84.6	86.0
-	Semi-supervised	-	86.5

Table 2: *Micro F-measure of the each experiment setting. (KG = knowledge graph, w-gaz = weighted gazetteer, * = uses a different set of features)*

with the following steps:

1. Train an implicit relation classifier on D_I.
2. Apply the implicit relation classifier on the queries in D_E and augment the predicted implicit relations to D_E.
3. Train a combined classifier on the augmented D_E.

The reason we train the final model on D_E is that from our observation, the queries in D_E have a more diverse distribution of both explicit and implicit relations. Step 2 above transfers the knowledge about implicit relations from D_I to D_E.

5. Experiments

5.1. Dataset

To evaluate our approach, we use the movie domain relation dataset from [32]. The dataset contains 3,338 training and 1,084 test examples. However, except for the supervised learning upper bound, we ignore the training examples and train the classifiers from the mined queries instead.

As mentioned earlier, we treat relation detection as a multi-class, multi-label classification problem. Each dataset example contains a transcribed query and one or more relations extracted from the annotated SPARQL database query. The dataset contains a total of 70 relations in total. The average number of relations per query is 2.58, and 9.5% of the queries are marked as out-of-domain. The original paper includes more information about the specifics of the dataset [32].

5.2. Results and discussions

Table 2 shows the micro F-measure of our experiments. Unless stated otherwise, we train classifiers using *icsiboost* [34], an adaptive boosting framework, with 10,000 iterations. We use common features for text classification including n-gram features ($n = 1, 2, 3$) and weighted gazetteer features calculated using the populated semantic graph [32].

Upper bound and baseline. As a crude upper bound, we perform supervised learning on the labeled training data, which unsurprisingly gives a high F-measure of 86.0%.

As a simple baseline, we only output the most frequent relation (*movie type*), which gives an F-measure of 27.6%. Another baseline is the previously published best result on this dataset [33], using web search snippets that include two related entities to mine data for explicit relations. The main focus of that work is weighing knowledge graph entity types and enriching relation patterns by using word embeddings based on dependency parses. The F-measure with that approach is reported as 43.3%.

Comparing URL sources. Using URLs from knowledge graphs gives slightly better results than using URLs from seed queries. During error analysis, we discover that many seed queries q_s point to irrelevant URLs due to the ambiguity of the entity name. For example, the comic character *Flash* produces the seed query *"flash movie,"* which generally refers to Adobe Flash movies and not the comic character. In future work, we want to investigate the ways to obtain more accurate URLs from seed queries using, for example, the click statistics from QCL.

We will now discuss the results where the URLs come from knowledge graphs.

Single relation type. The explicit relation classifier gives around 15% absolute increase in F-measure over the majority baseline. On the contrary, the implicit relation classifier gives relatively lower scores. This is mainly because there are fewer implicit relations than explicit ones, and the implicit relation classifier only covers 10 out of all 70 relations in the dataset.

Combined model. The combined model achieves the F-measure of 55.5%, which is significantly higher than the score from the explicit relation classifier. This means both explicit and implicit relation datasets help boost the performance of the classifier.

While the explicit relation classifier trained with the search query logs data results in a similar F-measure to the previous work that targeted explicit relations [33] (with an F-measure of 42.7% versus 43.3%), our combined model achieved a significantly better F-measure, showing the contribution of implicit relation classifier.

Semi-supervised learning. The bootstrapped classifier can also be used to improve the accuracy of the fully supervised model. By applying the best unsupervised classifier on the queries in the supervised learning dataset and use the predictions as additional features for supervised learning, we are able to slightly increase the F-measure from 86.0% to 86.5%.

6. Conclusions

In this work, we proposed an unsupervised method to bootstrap a relation classifier from knowledge graphs and query click logs. To mine natural language queries, we link the knowledge graph entities of interest to URLs using either the URL relations in knowledge graphs or the seed queries. Subsequently, we mine search queries from those URLs, label the queries with either explicit or implicit relations using different techniques, and then train relation classifiers with adaptive boosting. Apart from the classifier, we also get automatically labeled slots for explicit relations and query patterns for implicit relations as by-products. Our approach performs a significantly better F-measure (55.5%) than a natural baseline as well as previously published best results.

7. References

[1] G. Tur and R. De Mori, Eds., *Spoken Language Understanding: Systems for Extracting Semantic Information from Speech*. New York, NY: John Wiley and Sons, 2011.

[2] C. Raymond and G. Riccardi, "Generative and discriminative algorithms for spoken language understanding." in *INTERSPEECH*, 2007, pp. 1605–1608.

[3] D. Hakkani-Tur, L. Heck, and G. Tur, "Using a knowledge graph and query click logs for unsupervised learning of relation detection," in *Acoustics, Speech and Signal Processing (ICASSP), 2013 IEEE International Conference on*. IEEE, 2013, pp. 8327–8331.

[4] K. Bollacker, C. Evans, P. Paritosh, T. Sturge, and J. Taylor, "Freebase: a collaboratively created graph database for structuring human knowledge," in *Proceedings of ACM SIGMOD*, 2008.

[5] N. Craswell and M. Szummer, "Random walks on the click graph," in *Proceedings of the 30th annual international ACM SIGIR conference on Research and development in information retrieval*. ACM, 2007, pp. 239–246.

[6] Y.-Y. Wang, L. Deng, and A. Acero, "Spoken language understanding," *Signal Processing Magazine, IEEE*, vol. 22, no. 5, pp. 16–31, 2005.

[7] Y.-Y. Wang and A. Acero, "Discriminative models for spoken language understanding." in *INTERSPEECH*, 2006.

[8] P. J. Price, "Evaluation of spoken language systems: The ATIS domain," in *Proceedings of the DARPA Workshop on Speech and Natural Language*, Hidden Valley, PA, June 1990.

[9] Y.-N. Chen, W. Y. Wang, and A. I. Rudnicky, "Unsupervised induction and filling of semantic slots for spoken dialogue systems using frame-semantic parsing," in *Proceedings of IEEE Automatic Speech Recognition and Understanding Workshop (ASRU)*, 2013.

[10] A. Chotimongkol and A. Rudnicky, "Automatic concept identification in goal oriented conversations," in *Proceedings of ICSLP*, 2002.

[11] G. Tur, D. Hakkani-Tür, and A. Chotimongkol, "Semi-supervised learning for spoken language understanding using semantic role labeling," in *Proceedings of Proceedings of IEEE Automatic Speech Recognition and Understanding Workshop (ASRU)*, 2005.

[12] M. Mintz, S. Bills, R. Snow, and D. Jurafsky, "Distant supervision for relation extraction without labeled data," in *Proceedings of the Joint Conference of the 47th Annual Meeting of the ACL and the 4th International Joint Conference on Natural Language Processing of the AFNLP: Volume 2-Volume 2*. Association for Computational Linguistics, 2009, pp. 1003–1011.

[13] S. Riedel, L. Yao, and A. McCallum, "Modeling relations and their mentions without labeled text," in *Machine Learning and Knowledge Discovery in Databases*. Springer, 2010, pp. 148–163.

[14] R. Hoffmann, C. Zhang, X. Ling, L. Zettlemoyer, and D. S. Weld, "Knowledge-based weak supervision for information extraction of overlapping relations," in *Proceedings of the 49th Annual Meeting of the Association for Computational Linguistics: Human Language Technologies-Volume 1*. Association for Computational Linguistics, 2011, pp. 541–550.

[15] Q. Cai and A. Yates, "Large-scale semantic parsing via schema matching and lexicon extension." in *ACL*, 2013, pp. 423–433.

[16] J. Berant, A. Chou, R. Frostig, and P. Liang, "Semantic parsing on freebase from question-answer pairs." in *EMNLP*, 2013, pp. 1533–1544.

[17] X. Yao and B. Van Durme, "Information extraction over structured data: Question answering with freebase," in *ACL*, 2014.

[18] T. Joachims, "Optimizing search engines using clickthrough data," in *Proceedings of the eighth ACM SIGKDD international conference on Knowledge discovery and data mining*. ACM, 2002, pp. 133–142.

[19] H. Cui, J.-R. Wen, J.-Y. Nie, and W.-Y. Ma, "Probabilistic query expansion using query logs," in *Proceedings of the 11th international conference on World Wide Web*. ACM, 2002, pp. 325–332.

[20] R. Baeza-Yates, C. Hurtado, and M. Mendoza, "Query recommendation using query logs in search engines," in *Current Trends in Database Technology-EDBT 2004 Workshops*. Springer, 2005, pp. 588–596.

[21] S. Sekine and H. Suzuki, "Acquiring ontological knowledge from query logs," in *Proceedings of the 16th international conference on World Wide Web*. ACM, 2007, pp. 1223–1224.

[22] M. Komachi and H. Suzuki, "Minimally supervised learning of semantic knowledge from query logs." in *IJCNLP*, 2008, pp. 358–365.

[23] A. Jain and M. Pennacchiotti, "Open entity extraction from web search query logs," in *Proceedings of the 23rd International Conference on Computational Linguistics*. Association for Computational Linguistics, 2010, pp. 510–518.

[24] Y. Liu, M. Zhang, L. Ru, and S. Ma, "Automatic query type identification based on click through information," in *Information Retrieval Technology*. Springer, 2006, pp. 593–600.

[25] P. Pantel, T. Lin, and M. Gamon, "Mining entity types from query logs via user intent modeling," in *Proceedings of the 50th Annual Meeting of the Association for Computational Linguistics: Long Papers-Volume 1*. Association for Computational Linguistics, 2012, pp. 563–571.

[26] M. Paşca, "Queries as a source of lexicalized commonsense knowledge," in *Proceedings of the 2014 Conference on Empirical Methods in Natural Language Processing (EMNLP)*. Association for Computational Linguistics, 2014, pp. 1081–1091.

[27] D. Hakkani-Tur, L. Heck, and G. Tur, "Exploiting query click logs for utterance domain detection in spoken language understanding," in *Acoustics, Speech and Signal Processing (ICASSP), 2011 IEEE International Conference on*. IEEE, 2011, pp. 5636–5639.

[28] A. Celikyilmaz, D. Hakkani-Tür, and G. Tür, "Leveraging web query logs to learn user intent via bayesian discrete latent variable model," in *ICML*, 2011.

[29] J. Pound, A. K. Hudek, I. F. Ilyas, and G. Weddell, "Interpreting keyword queries over web knowledge bases," in *Proceedings of the 21st ACM international conference on Information and knowledge management*. ACM, 2012, pp. 305–314.

[30] A. Celikyilmaz, G. Tür, and D. Hakkani-Tür, "Isnl? a discriminative approach to detect natural language like queries for conversational understanding." in *INTERSPEECH*, 2013, pp. 2569–2573.

[31] G. Tür, M. Jeong, Y.-Y. Wang, D. Hakkani-Tür, and L. P. Heck, "Exploiting the semantic web for unsupervised natural language semantic parsing." in *INTERSPEECH*, 2012.

[32] D. Hakkani-Tür, A. Celikyilmaz, L. Heck, G. Tur, and G. Zweig, "Probabilistic enrichment of knowledge graph entities for relation detection in conversational understanding," in *Proceedings of Interspeech*, 2014.

[33] Y.-N. Chen, D. Hakkani-Tür, and G. Tur, "Deriving local relational surface forms from dependency-based entity embeddings for unsupervised spoken language understanding," in *Proceedings of IEEE Spoken Language Technology Workshop (SLT)*, 2014.

[34] B. Favre, D. Hakkani-Tür, and S. Cuendet, "Icsiboost," http://code.google.come/p/icsiboost, 2007.